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SIMULATION OF FORCED-VENTILATION FIRES

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Abstract

Fire hazard descriptions and compartment fire models are assessed as input to airflow network analysis methods that simulate the exposure of ventilation system components to fire products. The assessment considered the availability of hazard descriptions and models for predicting simultaneous heat and mass release at special compartment openings that are characterized by a one-dimensional and controllable volumetric flux.

I. Introduction

The airflow network analysis codes developed by the Los Alamos National Laboratory simulate the effects of tornadoes and explosions with source terms that describe heat and mass release to ventilation systems.^{(1),(2)} Extending the codes to fire accident simulation analysis requires prescribing heat and mass release from fires.⁽³⁾ Fire models are needed in this accident simulation to predict heat and mass exhaust from compartment openings. Therefore, available fire hazard classifications and models were assessed for their capability to simulate heat and mass exhaust from fire zones.

Industrial facilities usually have doors and windows that allow the smoke to escape before it descends to the fire. Thus, industrial fire protection and the associated fire models are concerned with efficient combustion in the presence of uncontaminated air and the bi-directional flow of both air and fire products through the same openings. Nuclear facilities use radioactivity barriers to protect employees and the public against the hazards of ionizing radiation. Filtered venting systems and associated forced ventilation are often installed to confine radioactive dust, and the same confinement is inadvertently imposed on smoke. Therefore, nuclear plant fire models are concerned with inefficient combustion in the presence of smoke (soot and low vapor pressure liquids) and with one-dimensional and controllable flow through compartment openings. They differ from industrial and building fires in the following ways (Fig. 1).

- (1) Bi-directional flow of fire products and air through one large opening is replaced by unidirectional flow in intake and exhaust openings.
- (2) Fire products descend to the seat of the fire. Therefore, fire plumes contain more reaction products and less fresh air.

There is a reasonable doubt that existing compartment fire data bases and compartment fire models will simulate adequately heat, toxic/corrosive gas, and particulate injection to the ventilation system adjacent to a fire zone. We evaluated available fire protection design standards and compartment fire models for their capability to simulate heat and mass release from forced ventilation fires. The assessment considered

- (1) coverage of fire hazards that are commonly used for the design of active fire protection systems and
- (2) the potential for existing fire models to be extended to forced ventilation situations.

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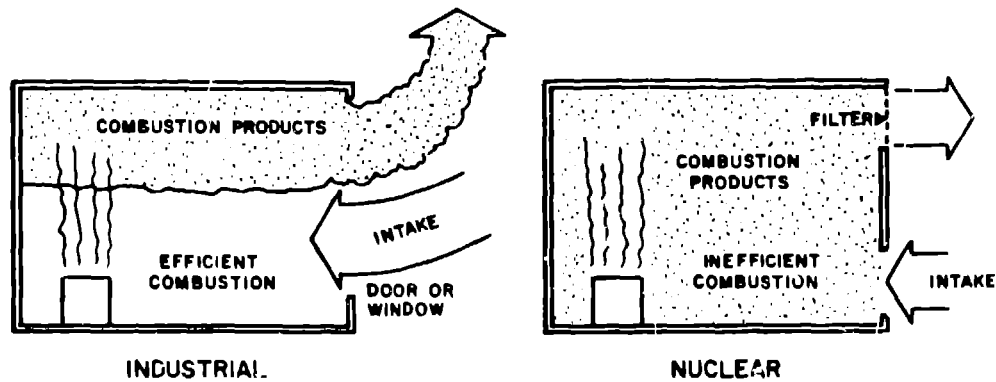


Figure 1. Difference between industrial and nuclear facility fires.

II. Requirements For Fire Accident Analysis

Volumetric exhaust flow rates usually are imposed by the ventilation system. Exhaust rates then are determined by the temperature and composition time history of the burn room atmosphere drawn into the ventilation system.

Analytical Requirements

In our opinion, a quantitative description of fire accidents requires the following tasks.

- (1) Quantify fire hazards in terms of heat and mass release at the seat of the fire.
- (2) Simulate temperature, oxygen, and fire product concentration transients in the burn room atmosphere as a function of volumetric exhaust and fire hazard.

The first task has to be addressed in the design of any fire ventilation and fire suppression system and denotes user requirements. The second task describes analytical requirements for the accident analysis use of compartment fire models. Both analysis requirements set the final performance criteria for any experimental or analytical simulation of forced ventilation fires.

User Requirements

The National Fire Protection Association (NFPA) uses a description of fire hazards when specifying the design, installation, and maintenance of fire-ventilation and fire-suppression systems.⁽⁴⁾⁻⁽⁷⁾ Standards for installation of smoke and heat venting systems classify fire hazards in terms of low, moderate, and high heat release.⁽⁴⁾ A quantitative description of associated heat release rates is implied by the minimum water discharge requirements for fire zones, which are given in Table I.⁽⁷⁾

Discharge requirements for gaseous fire suppression systems recognize that heat release per fuel decomposition are largely controlled by the type of combustible material.^{(5),(6)} The following four different fire types are specifically mentioned in NFPA fire suppression standards.

Pool Fires. Fire accident scenarios describe the spill of flammable working fluids, cleaning fluids, process chemicals, and so on.⁽⁵⁾⁻⁽⁷⁾ Halon fire-suppression standards call for analyzing the temperature dependence of flammable

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Table I. Fire hazard classification of NFPA 13-76.

Heat Release Classification	Minimum Water Supply, ^a gal/min/ft ²	Equivalent heat ^b absorption, kW/m ²
Low	.050 (0.034 L/s·m ²)	86
Moderate	.095 (0.064 L/s·m ²)	164
High	.137 (0.093 L/s·m ²)	237
Very high	.162 (0.110 L/s·m ²)	280

^aAssumes 4000 ft² (372 m²) sprinkler protection.

^bEvaporation of 1 gal H₂O absorbs 9.546 kW/s.

vapor concentrations.⁽⁷⁾ Fuel weight loss or mass burning rates are controlled by heat feedback from laminar and turbulent diffusion flames. Pool size can be used to differentiate between laminar and turbulent combustion.⁽⁸⁾

Surface Fires of Noncharring Solids. Porous plastic fuels such as foam or cable trays have emerged as the most significant fire accident hazards. Both gas and water are used for fire suppression. Active fire protection is needed because noncharring plastic may melt and sporadically achieve the high mass-burning rates that characterize liquid pool fires. Excess pyrolyzate from rapid volatilization can produce excessively long flames that promote rapid fire spread into adjoining fire zones.⁽⁹⁾ Mass burning rate is controlled by heat irradiation of the fuel and is strongly dependent on burn room gas temperature and composition.

Surface Fires of Charring Solids. Surface fires of charring solids are fire scenarios that describe the combustion of cellulosic materials such as wood, paper records, and clothes racks.⁽¹⁰⁾ The preferred fire-suppressing agent is water. Mass burning rates are controlled by char oxidation, which proceeds independently of temperature and composition of the burn room gas. This independence has been confirmed through analysis of over 250 full-scale and reduced-scale compartment burn tests.⁽¹¹⁾

Deep-Seated Fires. Deep-seated fires are isolated inside porous solid fuels such as plastic foams, record files, mattresses, and cable trays. The isolation makes deep-seated fires very difficult to detect. It also makes delivering fire-suppression agents to the seat of the fire very difficult. Although the rate of heat and mass release from deep-seated fires is low, it may still present a significant threat to ventilation systems because fuel vapor release may persist undetected for long periods of time and be mixed with ambient fresh air. Deep-seated fires also have been identified as one key to fire spread through reignition of surface fire during readmission of fresh air.⁽¹²⁾

Spray Fires. The above broad classification of fire hazards summarizes building and industrial plant fires. Also, nuclear facilities have combustible working fluids under pressure that would produce a fuel spray during an inadvertent break of a pressurized system. The most frequent fire accident that has required shutting down a reactor involves reactor coolant pumps, and the most common fuels involved are lubricating oils and electrical insulation materials.⁽¹³⁾ The

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international Committee for the Safety of Nuclear Installations has placed spray fires as a fifth class of important fire hazards.⁽¹⁴⁾

Based on the above survey of fire protection design hazards, preliminary user requirements for fire accident analysis are formulated as follows.

- (1) Provide compartment fire model inputs of heat and fire product release rates for the following classes of fire hazards.
 - Spray fires
 - Pool fires
 - Surface fires of noncharring solids
 - Surface fires of charring solids
 - Deep-seated fires
- (2) Simulate fire growth and recession, which are caused by the dependence of fire heat and mass release rates on the temperature and composition of the burn room atmosphere outside the fire plume.

III. Preliminary Assessment of Compartment Fire Models.

The development of analytical fire models is an active and progressive field. A comprehensive review of models in use and model updates was beyond the initial scope of our fire model assessment program. Instead, we selected seven multilayer models according to personal knowledge and informal professional contacts. The following models were reviewed.

- University of California Berkeley (UCB) model⁽¹⁵⁾
- Harvard model⁽¹⁶⁾
- Canada model⁽¹⁷⁾
- National Bureau of Standards (NBS) model⁽¹⁸⁾
- Illinois Institute of Technology Research Institute (IITRI) model⁽¹⁹⁾
- Japan model⁽²⁰⁾
- California Institute of Technology (Caltech) model⁽²¹⁾

The associated references may not reflect the most recent developments in these models, and we hope that the reader will call our attention to both models and updates that should be included in the continuing assessment of analytical fire models.

Screening Criteria

Models were screened for simulation of forced ventilation, number and type of predicted burn room transients, and compatibility with user analysis requirements. The results of this review are summarized in Table II and are explained as follows.

Simulation of Forced Ventilation

All seven of the reviewed models describe bi-directional flows of air and fire products through a large uncontrolled opening (window or door). They are not designed to simulate forced ventilation. However, Creighton showed that a unidirectional exhaust flow can be simulated by using a fictitious second room, as shown in Fig. 2.⁽²²⁾ Thus, capabilities for simulating forced ventilation are available indirectly in any building fire model that has a multiroom capability. As shown in Table II, such a capability exists only for the most simple fire models, which ignore radiation. Available fire models may have a capability to simulate forced ventilation spray fires, surface fires of charring materials, and deep-seated fires. However, simulation capabilities for forced ventilation of pool

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Table II. Overview of available models.

Originator(s) Institution	Forced Ventilation	Number of Simultaneous Transients	Radiation Exchange	Systematic Verification by Test	Advantages/ Disadvantages
Brabauskas UCB	Yes	1 of 3	No	No	2, 3, A, B, D
Emmons Harvard	No	3 of 3	Yes	Yes	3, A, C
Harmathy Canada	No	1 of 3	No	Yes	1, 2, 3, 4, A, B, D
Krause Los Alamos	Yes	3 of 3	No	New Model	2, 3, 4, D
Quintieri NBS	No	1 of 3	Yes	Yes	1, 3, C
Waterman, Page IITRI	No	2 of 3	Yes	Yes	1, 2, 3, A, C
Tanaka Japan	Yes ^a	1 of 3	No	New Model	2, 3, 4, C
Zukoski/Alvares/ Creighton Caltech	Yes ^a	2 of 4	No	New Model	2, 3, 4, A

ADVANTAGES

1. Model parameters summarize many tests
2. Simplicity
3. Research basis for fire control
4. Multiple burn mode potential

DISADVANTAGES

- A. Lacks distinction of fire hazards
- B. Limited to ventilation-controlled fires
- C. Lacks ventilation system interface
- D. Uncertain for bi-directional flow

^aRequires "fictitious" room to represent unidirectional exhaust.

fires and surface fires of noncharring materials will most likely need additional research and development because both radiation exchange and forced ventilation must be simulated.

Spray fires are most easy to model without additional research and development because the spray release rate may be independent from the state of the burn room atmosphere. Thus, spray fires may be investigated without complex instrumentation and radiation exchange models. The spray fire results also may be applicable to surface fires or charring materials and deep-seated fires, which are equally independent from the state of the burn room atmosphere.

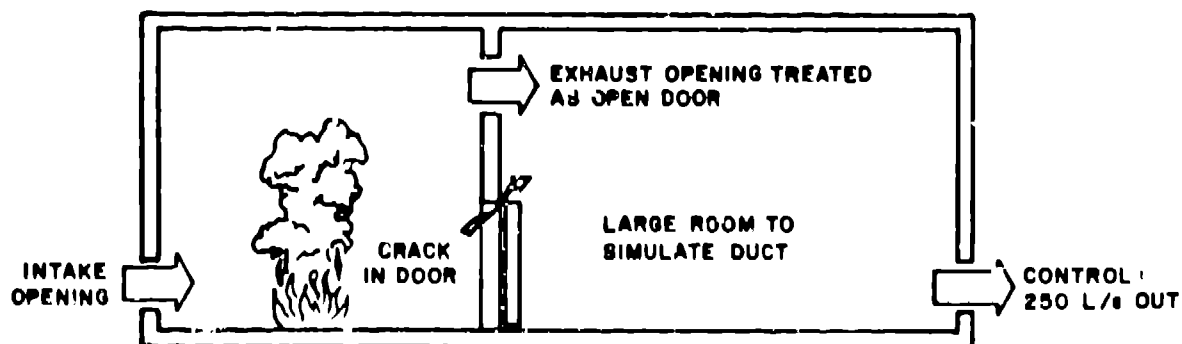


Figure 2. Caltech model simulation of ventilation-controlled exhaust opening.

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We restricted the following preliminary assessment of fire models to spray fires because this choice reduces the complexity and maximizes the utility of results for other fire hazards. The restriction to spray fires also allows us to directly compare simple fire models that do not simulate radiation with higher-level fire models that do. In addition, the number of available fire models is enlarged.

Simulation of Burn Room Transients

As discussed above, existing methods of ventilation systems analysis require simultaneous time histories of temperature, oxygen concentration, and fire product concentration in the upper or hot layer of the burn room. Models were screened for their ability to predict these fire zone transients. Bulk "fire product" was defined as total mass density minus gaseous oxygen and gaseous nitrogen. This idealized fire product includes both combustion products (such as CO_2 , CO , H_2O , and soot) and unburned components of the volatilized fuel (such as inert components and excess pyrolyzate). A model was credited with simulating fire product transients if it addressed the bulk fire product, CO_2 , or soot.

Table II shows that simple layer fire models are restricted to gas temperature predictions (one out of three), whereas models with radiation exchange capabilities sometimes track soot and CO_2 concentrations (two out of three). We did not find a simple two-layer model that ignores radiation but still simulates both oxygen and fire product generation. Because such a model is essential for the simulation of forced ventilation spray fires, we developed such a model. This new forced ventilation fire model is included in Table II.

Compatibility with User Requirements

A single-compartment fire model alone cannot simulate the fire hazards described above. To illustrate, the new Los Alamos fire model has no capability to simulate bi-directional flows, flames, and heat loss to the fuel. Building fire models do not simulate ventilation control, oxygen, and burn product concentrations. All of these parameters are simulated by the Los Alamos fire model. Thus, a second and more detailed evaluation of compartment fire models was initiated to find out whether models could be modified and integrated to simulate all fire hazard classes. Preliminary screening criteria are given in Table II. The ratings represent our current subjective judgment and will be confirmed or amended by comparing test predictions with forced ventilation fire tests.

IV. Simulation of Forced Ventilation Spray Fires.

Los Alamos and the Lawrence Livermore National Laboratory (LLNL) coordinated their independently sponsored fire research programs to share existing capabilities for simulating forced ventilation spray fires. Model selection was based on the readiness of models to predict forced ventilation spray fires ahead of the test. Selected models then were assessed by comparing predictions with those from other models and with the tests.

Experimental Simulation

All fire tests were conducted in the LLNL fire test facility shown in Fig. 3. The tests used nonsmoking fuels, that is, methane, methanol, and isopropanol, and the test method was borrowed from previous filter plugging tests.⁽²³⁾ The main drawback of this approach is that volumetric exhaust and composition gases are

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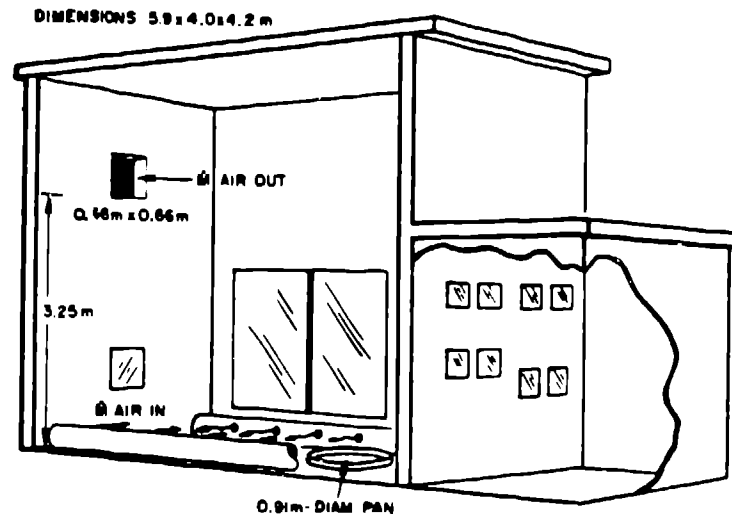


Figure 3. Lawrence Livermore National Laboratory burn room.

measured at the downstream high-efficiency particulate air (HEPA) filter end of a 9.75-m-long duct where exhaust temperatures have cooled to approximately 100°C. Information on composition in the hot layer and exhaust duct inlet was not available.

Individual fires were characterized by nominal fire strength (expected heat release in kilowatts) and nominal ventilation strength (expected volumetric exhaust flow rate at the HEPA filter in liters per second). A summary of the fires that are being used in our current assessment is given in Table III.

Table III. Preliminary verification of maximum temperature^a predictions by Caltech and Los Alamos fire models.

Fire Strength (kW)	25	50	50	200	200	400	400	800	800
Forced ventila- tion (L/s)	250	250	500	250	500	250	500	250	500
Fuel Composition	← Methane →			← Propyl Alcohol →					
CALTECH/ Bjstad	---	175	110	157	103	305	575	---	---
CALTECH/ Creighton	60	183	111	627	357	1270	681	---	---
CALTECH/ Zukoski	---	144 to 168	86 to 584	486 to 263	311 to 1156	977 to 586	496 to ---	---	---
Los Alamos/ Krause	173	219	184	229	185	280	229	285	280
Experiment/ Alvaras ^c	80	125	120	138	128	190	175	270	210

^aTable temperatures are in °C.

^bUsing heat deposition input from Los Alamos model.

^cVertical temperature profile averaged over hot layer.

Analytical Simulation

Fire modeling groups at several institutions were asked to predict the planned tests. The modeling groups were asked to predict eight fire tests that were characterized by combustion heat release (50 kW, 100 kW, 200 kW, and 400 kW) and two controlled exhaust flow rates (250 L/s and 500 L/s). Model predictions were made ahead of the test by J. Bolstad (Los Alamos, Caltech model), J. Creighton (LLNL, Caltech model), F. Krause (Los Alamos, Los Alamos model), and E. E. Zukoski (Caltech, Caltech model). The Caltech and Los Alamos models were selected for the initial assessment. The results of the pretest predictions are summarized in Table III for the hot-layer temperature.

The major differences in these predictions are the assumed amount of heat deposition in the burn room gas. Heat deposition refers to the difference between enthalpy flux out (exhaust) and enthalpy flux in (air intake + spray). Creighton assumed that the total heat of combustion goes into the gas. This assumption overestimated the hot-layer temperature by the largest margin. Zukoski allowed for some heat loss to the wall, which was based on professional judgment and open-door fire tests. Resulting hot-layer temperatures are lower than Creighton's estimates but are still much too large for the recirculation time period. Bolstad and Krause estimated heat depositions by back-calculating previous fire tests. These predictions are much more reasonable but circumvent the unresolved problem of input selection. Comparing the pretest predictions illustrates the importance of input assumptions on heat deposition during fire product recirculation and also illustrates the large uncertainty of these inputs.

Krause estimated heat deposition in the gas by back-calculating previous crib fire tests. These predictions showed that 50-kW and 100-kW fires would be too weak to generate any burn product descent and that the burn product from the 200-kW fire would descend only 23% of the ceiling-to-fuel-top distance. Bolstad used these same heat deposition estimates.

In the case of weak fires, heat deposition was not available and convective heating rates were assumed to vary between 10% to 20% of the combustion heat release. With these inputs, the Caltech model predicted that the burn products would always descend close to the floor no matter how weak the fire is.

The very first tests at LLNL used methane spray with fire strengths of 25 kW and 50 kW. Visual observation of temperature-profile displays showed that transparent burn products did descend partially although they did not descend close to the floor. Thus, we concluded that crib fires simulate spray fires poorly. A new set of heat deposition inputs was chosen by back-calculating the 25-kW methane fires. We could make the burn product descend very slightly (2.5%), but we could not match the observed ceiling temperature (178°C that was calculated vs the 80°C determined experimentally).

The above comparison of the pretest predictions clearly shows that neither the Caltech model nor the Los Alamos model is ready for spray fire predictions. Usable fire models would need a reliable method for predicting the final heat deposition in the gas either from laboratory tests or from thermodynamic principles. Given reliable inputs, available models still must be updated to more correctly describe the partial descent of fire products during weak or over-ventilated fires. Back-calculation of heat deposition from previous fire tests in the same facility is not acceptable for a ventilation systems analysis where variation of burn room architecture and ventilation strength is one of the major user requirements.

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Comparison of Predicted and Measured Burn Room Transients

Comparison of predicted and measured burn room transients is based on model predictions that use the back-calculated heat deposition values. This means that all Caltech model predictions were repeated after the tests by using heat deposition time history inputs that were produced by pretest predictions with the Los Alamos model. In this way, the comparison of the two models reflects the difference in fire physics assumptions and not individual opinions on model inputs.

The following subsection discusses the comparison of modeled and predicted fires for only one test that is typical for stronger fires (200 kW and more). Similar discussions of the other fire tests were omitted for brevity because both models and test methods are far from being finalized. Analytical simulations must be updated with better heat deposition estimates and experimental simulation must include sampling stations in the hot layer and/or the exhaust duct inlet. However, the conclusions do reflect information from all tests and not just from the one test used for illustration.

Heat Deposition in the Gas. Heat deposition in the burn room gas is an output from the Los Alamos model pretest prediction and an input to the Caltech model. The time history of the pretest prediction is shown in Fig. 4. However, there is no known experimental way to measure heat deposition directly. Comparison with experiments is indirect and is based on a convergence of evidence. Experimental evidence for heat deposition is available from heat release oven tests and from air intake measurements.

E. Smith and A. Tewarson have developed heat release ovens to measure the apparent heating value and generation rates of combustible vapors, smoke, toxic products, and corrosive products.^{(24),(25)} Scalability of generation rates is tested by repeating the small-scale (10-cm by 10-cm by 10-cm test sample) combustion test at intermediate scale (.3-m by .3-m by 4.3-m high samples) and large scale (3-m x 3-m x 3-m).⁽²⁵⁾

The majority of generation rates proved to be both reproducible and scalable. Data obtained so far indicate that simulation and testing of site-specific non-charring materials may not be necessary because materials could be classified in

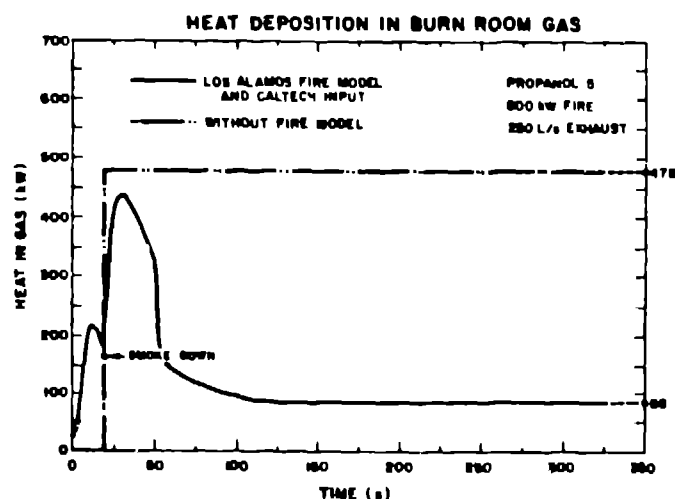


Figure 4. The prediction of the heat deposition in the burn room gas.

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four groups based on chemical structure (nonaromatic, nonaromatic/aromatic, aromatic, and highly halogenated fuels). Thus, Tewarson's test method provides an important first step for simulating heat and mass release for noncharring materials. Smith oven tests have accumulated similar information on a large variety of materials and also might be used as soon as the scalability of release rates has been confirmed.⁽²⁴⁾

A preliminary method for converting Tewarson's test results into heat disposition has been outlined by P. C. Owczarski.⁽²⁶⁾ The key assumption is that fires will rapidly grow to a stationary stage, which reflects the release rates per fire area that are measured in release rate oven tests. The release rates at fire zone openings then are step functions.

Using the step-function approximation, heat convection (\dot{Q}_c) through fire zone openings can be calculated from Tewarson's empirical data for convective heat release efficiencies.

$$X_c = \frac{\dot{Q}_c}{\dot{m}H_f}, \quad (1)$$

where H_f (kilojoules per gram of fuel) denotes the apparent heating value of the fuel and \dot{m} denotes the spray injection rate (g/s). This estimate of convective heat release describes the difference between ingoing and outgoing enthalpy fluxes.

$$\dot{Q}_c = \underbrace{\rho_h C_{ph} T_h \dot{V}_{ex}}_{\text{(hot exhaust)}} - \underbrace{\rho_a C_{pa} T_a \dot{V}_{in}}_{\text{(air intake)}} - \underbrace{C_{pf} T_f \dot{m}}_{\text{(fuel intake)}}, \quad (2)$$

where ρ denotes density, C_p denotes heat capacity, and \dot{V} denotes volumetric flux. The subscripts (h, a, f, ex, and in) are explained by the labels.

The step function of Fig. 4 illustrates the pretest prediction of the heat deposition in the gas that was made by extrapolating Tewarson's data. Proponal is also a nonaromatic fuel, and its convective heat-release efficiency should closely match that of other nonaromatic fuels. We use the value $X_c = .6$, which was selected by Mishima for nonaromatic fuels.⁽²⁷⁾ The mass burning rate \dot{m} is given in terms of the nominal fire strength (\dot{Q}_n),

$$\dot{Q}_n = H_f \dot{m}.$$

Extrapolation of heat release oven tests is given by

$$\dot{Q}_c = .6 \dot{Q}_n. \quad (3)$$

This value represents the step function of Fig. 4. The step was placed at the time the fire products are within the vicinity of the floor. At this "smoke down" time, the burn room has filled with heat-absorbing substances, and heat deposition in the gas should be a maximum because the hot layer gas temperature is still cool that is, wall heat losses are still small.

The main difference between the direct extrapolation of heat release rate oven tests and the Los Alamos fire model is the duration of the peak. The fire model predicts that heat deposition in the gas will recede quickly from its peak value while the burn room gas gets hot, although the oven tests do not simulate such an increase of heating loss.

Additional experimental evidence of heat deposition may be obtained by converting the predicted heat deposition \dot{Q}_c , which cannot be measured directly, to air intake predictions that are measured directly. Mathematically, this means that we have to solve Eq. (2) for the intake flux \dot{V}_{in} . The temperatures in the hot layer (T_h), the ambient air (T_a), and the volatilized fuel (T_f) are coupled by the isobaric condition of the fire zone. Neglecting the weak dependence of the molecular degrees of freedom on combustion product chemistry, we can approximate this coupling by using the following equation of state.

$$C_{ph}T_h\rho_h = C_{pa}T_a\rho_a = C_{pf}T_f\rho_f = 3.5 p \quad (4)$$

where p denotes the hydrostatic pressure.

Substituting Eq. 4 into Eq. 2 and solving for \dot{V}_{in} gives

$$\dot{V}_{in} = \dot{V}_{ex} - \frac{\dot{Q}_c}{3.5p} - \frac{\dot{Q}_n}{H_f \rho_f} \quad (5)$$

Thus, the intake flux is linearly proportional to the heat deposition in the gas in forced ventilation fires with the volumetric exhaust \dot{V}_{ex} is held constant. Figure 5 shows the time history of the intake flux that was calculated using heat deposition shown in Fig. 4 according to Eq. (5) with the handbook value $H_f = 33.2$ kJ/g. This curve is labeled "Los Alamos Fire Model" and reflects the physical assumptions of Eq. (4). The assumptions of the Caltech model, although considerably more complex, lead to a similar result. Both models appear to be roughly equivalent and bracket the final intake flux. Based on this evidence, the predicted heat deposition time history of Fig. 4 appears to be a reasonable approximation of the real heat deposition. The sharply peaked and transient nature of this heat deposition is surprising because both the mass burning rate and the volumetric exhaust \dot{V}_{ex} are held constant throughout the test.

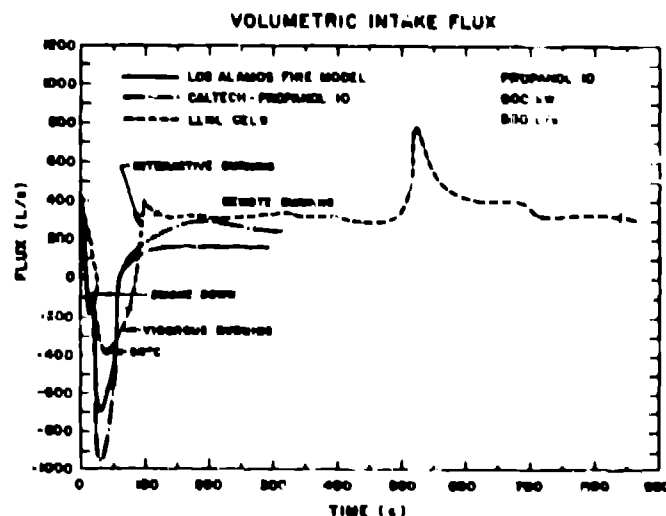


Figure 5. Comparison of intake fluxes.

The negative intake flux in Fig. 5 indicates that gases are blowing out of the intake opening; that is, the estimated amount of convective heat release can be accommodated only by flow reversal in the intake duct. A negative intake cannot exist for an extended time period because the fire will terminate through oxygen starvation. Thus, heat release oven tests are useful to estimate the transient peak heat deposition in the initial stages of the fire that will end with the descent of the fire products. However, heat release ovens do not adequately simulate the final stage of heat deposition.

Burn room temperatures. Burn room temperature profiles show the extent of the hot layer as indicated in Fig. 6. The time history of the near-ceiling temperature shown in Fig. 7 is also an important indicator of fire growth and fire recession.

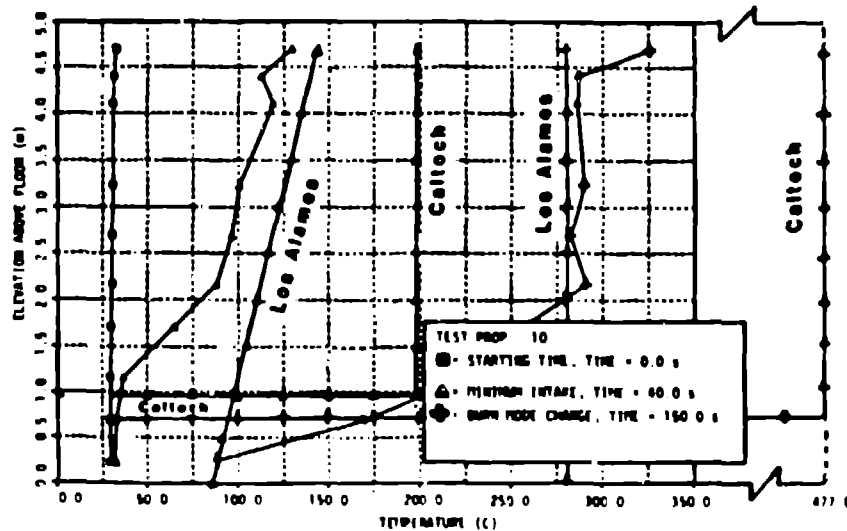


Figure 6. Temperature stratification, empirical events.

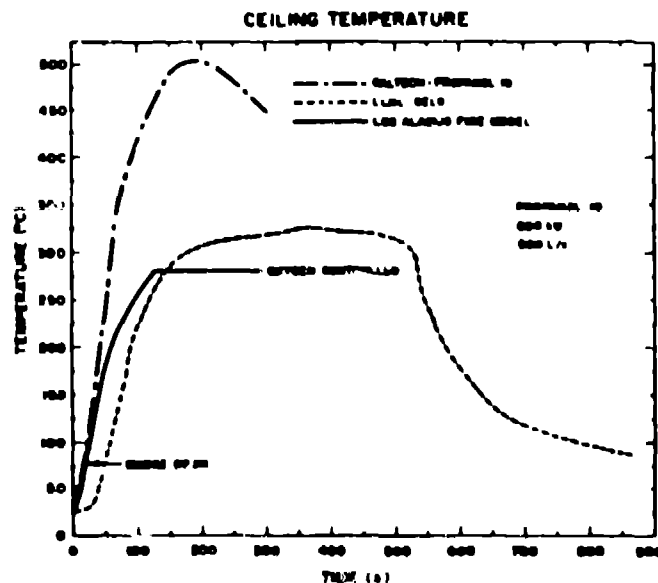


Figure 7. Comparison of ceiling temperatures.

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The measured temperature profiles of Fig. 6 are plotted for special event times that represent minimum air intake and burn mode transition (strongest curvature of the near-ceiling temperature-time history). See Fig. 7. A comparison of measured and predicted temperature profiles shows that the fire products do not descend all the way to the floor, as assumed by the Los Alamos model, but leave a cool layer, as assumed by the Caltech model. However, this layer is almost twice as thick as predicted by the Caltech model. Hot-layer temperatures are over-predicted by the Caltech model, whereas the Los Alamos model gives a reasonable approximation.

The temperature-time history in Fig. 7 shows rapid fire growth for about 110 s after the fire product descent has stopped. The stationary fire exists from 140 s to 540 s and then is followed by fire recession.

Using the Los Alamos model, we speculated that the stationary fire stage would be characterized by oxygen starvation, which is initiated by a time-limited period of intake flow reversal. This speculation is based on a residual oxygen concentration of 13% that characterized the self-termination of flammable liquid fires in water-sealed compartments.⁽²⁸⁾ This speculation is not born out by the test as shown by the measured oxygen concentration time history in Fig. 8. Apparently, heat deposition in the gas is limited entirely by wall heat losses and not by an oxygen-controlled decrease of combustion efficiency.

NFPA, after reviewing many compartment fire tests with an open door or window, postulated building fire growth stages that are based on ceiling temperature and combustion heat release as shown in Table IV.⁽²⁹⁾

Comparing the qualitative fire growth classification with the heat deposition of Fig. 4 and ceiling temperature of Fig. 7, we concluded that minimum intake coincides with vigorous burning and fire growth is associated with interactive burning. The stationary fire might be associated with remote burning provided the temperature threshold of remote burning is lowered from 400°C to 300°C. There are no remote pieces of furniture in the LLNL burn room, and remote burning (if it exists) would describe the ignition of remote fuel vapor accumulations in the hot layer. The instability of the intake flux after 450 s (Fig. 5) may support such speculation. Intake flux instability is more pronounced in weaker fires where the hot layer contains more oxygen.

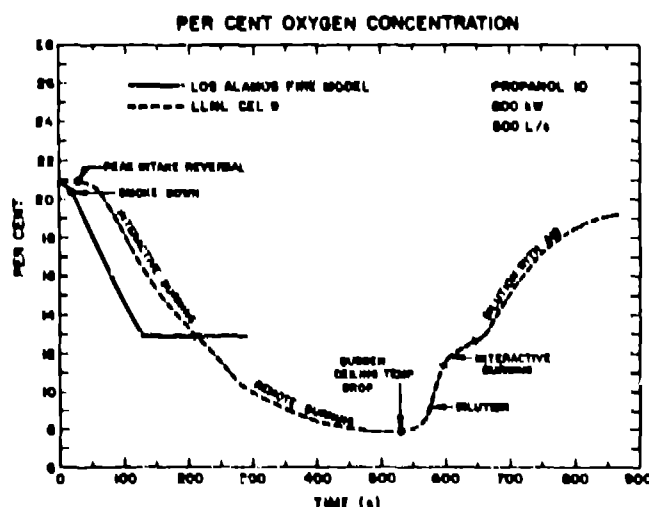


Figure 8. Comparison of oxygen concentration.

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Table IV. NFPA classification of fire growth phenomena.

<u>State</u>	<u>Phenomenon</u>	<u>Thermodynamic Definition</u>
1	Preburning	No flames.
2	Sustained burning	Ignition (including smoldering) has occurred in the room of origin, but heat release rate does not exceed 2 kW.
3	Vigorous burning	Heat release rate inside the room of origin is between 2 and 50 kW, but the upper peak room temperature is less than 150°C.
4	Interactive burning	Average upper room temperature is between 150°C and 400°C, causing secondary ignitions beyond the room of origin but with heat release less than 2 kW.
5	Remote burning	Average temperature in room of origin is greater than 400°C, causing secondary ignitions beyond the room of origin with heat release of less than 2 kW.
6	Full room involvement	Burning beyond the room of origin releasing 2 to 50 kW; secondary fires have reached state 3 conditions.

Hot layer oxygen concentrations. Oxygen concentrations measured at the HEPA filter would be representative of the oxygen concentration in the hot layer, provided the composition of the exhaust gas does not change in the duct and the duct does not entrain outside air through leaks.

Figure 8 shows the comparison of measured and predicted oxygen concentrations. The measured curve is labeled with the NFPA burn mode classification assuming ceiling temperature thresholds of 150°C and 300°C. The label "dilution with air" refers to any time period during which oxygen concentration increases and temperatures decrease. The comparison shows that predictions of oxygen concentration time histories are reasonable above the assumed threshold of 13%.

The experimental curve goes to concentrations below the 13% threshold, and the transition threshold is marked by a transition from interactive to remote burning. Similar coincidences of residual (sealed self-termination) oxygen thresholds and fire growth stages are found in the other tests. Unfortunately, the data base is insufficient to confirm that NFPA criteria for fire growth may be extended to forced ventilation fires.

Fire product concentration. Fire product concentrations are important in nuclear facilities analysis because product release outside the fire zone may clog filters, produce health hazards, corrode sensitive electrical contacts or detectors, and produce acid waste water. Fire product concentrations are also the cornerstone for verifying the Los Alamos fire model because the model is based on a solution of the fire product balance equation.

Fire product concentration is defined as total hot-layer mass concentration (100%) minus concentrations of residual oxygen and nitrogen gas. Thus, "fire product" denotes all foreign mass other than air and is made up of unburned fuel (excess pyrolyzate) as well as all products of combustion. In the LLNL tests, fire product components are CH_x , smoke particles, CO_2 , H_2O , and CO .

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The LLNL tests directly measured CH_x equivalent CH_4 , CO_2 , and CO concentrations. Time histories of H_2O concentrations were assumed to be directly proportional to CO_2 concentrations. The factors of proportionality for methane (.82) and propanol (.72) fuel were estimated assuming stoichiometric combustion that produces only CO_2 and H_2O . Smoke concentration was ignored because methane and propanol usually burn lean (without generating any visible smoke). Our neglect of smoke is uncertain during periods of remote burning where visual observation indicated the formation of a black but still transparent smoke.

Figure 9 shows a comparison of predicted and measured fire product concentrations. The experimental curves were calculated by adding measured CO_2 , CO , and CH_4 concentrations to estimated H_2O concentrations. All curves are labeled according to the burn-mode transitions that were discussed in preceding sections.

The comparison of experimental and predicted fire product concentrations also shows a reasonable agreement for interactive burning. One intriguing new fact is that experimental oxygen and fire product concentrations are mirror images of each other. This may indicate that nitrogen mass concentration is constant because depleted oxygen is replaced by fire products.

V. Summary and Conclusions

1. A method for simulating fire product exposure of ventilation system components should meet the following performance requirements.
 - Provide model inputs on heat and fire product release rates for spray fires, pool fires, surface fires of noncharring materials, surface fires of charring materials, and deep-seated fires.
 - Simulate temperature and composition transients of the burn room atmosphere for each of the above hazards as well as for fire growth and recession, which is caused by heat and mass release dependence on atmospheric transients.
2. A review of seven building fire models showed that multiroom models may be manipulated to simulate forced ventilation by replacing unidirectional exhaust flow with a fictitious second room. However, all multiroom models lack the capability to simulate burn room transients of oxygen concentration and fire

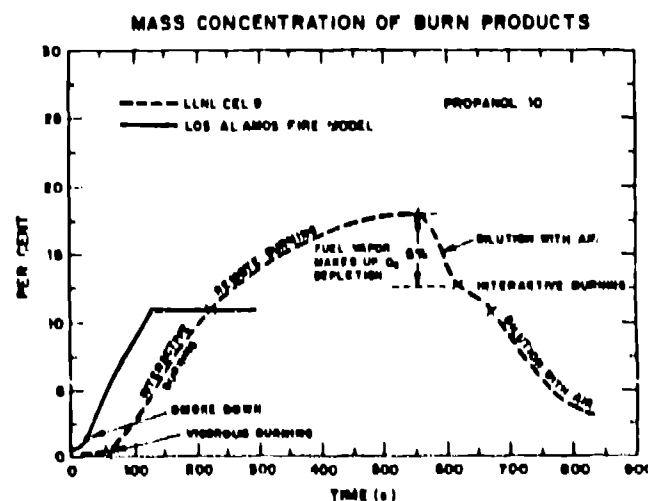


Figure 9. Comparison of burn product concentrations.

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product concentration. Burn room composition transients are partially simulated by higher-level building fire models that simulate radiation exchange. However, at present none of the high-level models can simulate forced ventilation. Existing building fire models are not designed to simulate spray fires, surface fires of charring materials, and deep-seated fires.

3. Pretest predictions of forced ventilation spray fires were made with the Caltech and Los Alamos fire models. The comparison of the pretest predictions showed that
 - forced ventilation fires are characterized by a highly time-varying heat deposition in the burn room gas that peaks at the time when the descent of the fire products is stopped and
 - the final stationary rate of heat deposition is smaller by a factor of 3 to 5 than estimates based on the extrapolation of heat release tests.
4. A comparison of predicted and measured burn room transients showed the following.
 - Two-layer building fire models and the Los Alamos fire model show promise to predict both temperature and composition transients of the burn room atmosphere for spray fires, surface fires of charring materials and deep-seated fires.
 - The Caltech and Los Alamos models are not ready to simulate forced ventilation fires. The following simulation capabilities must still be developed and demonstrated.
 - (1) Partial fire product descent for moderately strong fires
 - (2) Spray fire of smoky fuels
 - (3) Burn room transients caused by oxygen starvation
 - (4) Heat and mass release input selection for fire hazards other than fuel spray

References

1. K. H. Duerre, R. W. Andrae, and W. S. Gregory, "TVENT, a computer program for analysis of tornado-induced transients in ventilation systems," Los Alamos Scientific Laboratory report LA-7397-MS (July 1978).
2. P. K. Tang, W. S. Gregory, and C. Ricketts, "A numerical and experimental investigation of simulated explosions inside a flow network," Los Alamos National Laboratory report LA-9340-MS (May 1982).
3. R. W. Andrae, J. W. Bolstad, W. S. Gregory, F. R. Krause, R. A. Martin, and P. K. Tang, "FIRAC users manual - a computer code for fire-induced flow and material transport in nuclear facilities," Los Alamos National Laboratory report in preparation.
4. National Fire Protection Association, "Smoke and heat venting," NFPA No. (204) (NFPA, Boston, 1968).
5. National Fire Protection Association, "Standard on carbon dioxide extinguishing systems," NFPA 12-77 (Boston, 1976).
6. National Fire Protection Association, "Standard on halogenated fire extinguishing agent systems, NFPA-12A-77 (Boston, 1977).
7. National Fire Protection Association, "Standard for the installation of sprinkler systems," NFPA 13-76 (Boston, 1976).

17th DOE NUCLEAR AIR CLEANING CONFERENCE

8. A. Tewarson, "Flammability of polymers and organic liquids - part I, burning intensity," Factory Mutual Research Corporation, Norwood, MA, Technical Report No. 22429 (February 1975).
9. P. I. Pagni and T. M. Shi, "Excess pyrolyzate," 16th Int. Symposium on Combustion, The Combustion Institute (Pittsburgh, PA, 1976), pp. 1329--1342.
10. R. Friedman, "Ignition and burning of solids," Fire Standards and Safety, American Society for Testing and Materials report ASTM-STP 614 (1977), pp. 91--111.
11. T. Z. Harmathy, "Mechanism of burning of fully developed compartment fires," Combustion and Flame 31, 265-273 (1978).
12. F. R. Krause and W. H. Schmidt, "Burn mode analysis of horizontal cable tray fires," NUREG/CR-2431 (February 1982).
13. T. L. Buckley, L. M. Krasner, and S. A. Wienot, "Evaluation of fire hazards in nuclear power generation structures," Factory Mutual Report FMRC No. 22512, Norwood, MA (May 1976).
14. L. Clark, "Technical note on the nuclear fuel cycle facilities sub group meetings, April 27-29, 1982," Committee on the Safety of Nuclear Installations, OECD, Nuclear Energy Agency, Paris, France (May 1982).
15. V. Babrauskas, "COMP F - A program for calculating post-flashover fire temperatures," University of California, Berkeley report UCB FRG 75-2 (January 1975).
16. H. E. Mitler and H. W. Emmons, "Documentation for CFC V, the fifth Harvard computer fire code," National Bureau of Standards report, NBS Grant No. G7-9011 (October 1981).
17. T. Z. Harmathy, "Effect of the nature of fuel on the characteristics of fully developed compartment fires," Fire and Materials 3, 49-60 (March 1979).
18. J. Quintieri, "Growth of fire in building compartment," Fire Standards and Safety, ASTM STP 614 (American Society for Testing and Materials, Philadelphia, 1977), pp. 133-165.
19. R. Pape, J. Mavic, D. Kalkbrenner, and T. Waterman, "Semistochastic approach to predicting the development of a fire in a room from ignition to flashover, program documentation and users guide," National Bureau of Standards report NBS-GCR-77-111 (June 1976).
20. T. Tanaka, "A model on fire spread in small scale buildings, 2nd report," Japan Ministry of Construction, Building Research Institute, BRI paper 84 (March 1980).
21. E. E. Zukoski and T. Kubota, "Two layer modeling of smoke movement in building fires," Fire and Materials, 4, 17-27 (1980).
22. J. Creighton, private communication (June 1981).

17th DOE NUCLEAR AIR CLEANING CONFERENCE

23. N. Alvaras, D. Beason, V. Bergman, J. Creighton, H. Ford, and A. Lipska, "Fire protection countermeasures for containment ventilation", Lawrence Livermore National Laboratory Progress report UCID-1878 (September 1980).
24. E. E. Smith, "Measuring rate of heat, smoke and toxic gas release," Fire Technology, 8 (3), 237 (1972).
25. A. Tewarson, "Physics - chemical and combustional pyrolysis properties of polymeric materials," Factory Mutual Research Corp., Technical Report OEON6RC (November 1980).
26. P. C. Owczarski, M. K. W. Chan, M. Y. Ballinger, J. Mishima, "Level one source term models for fires," Fuel Cycle Facility Accident Analysis Handbook, Battelle Pacific Northwest Laboratory draft report NUREG TCR-2508 (May 1982).
27. J. Mishima, "Small scale fire problem: fire in slugging press enclosure, revision, Battelle Pacific Northwest Laboratories memorandum on project A-97515 (June 18, 1981).
28. R. S. Algier and S. J. Wiersma, "Ship fire characteristics, part 1: sealed compartments," Naval Surface Weapons Center report NSWC/NGL TR 76-125 (November 1976).
29. G. N. Berlin, E. M. Conelly, R. Fahey, D. D. Russel, and J. A. Swartz, "Fire safety analysis for residential occupancies," National Fire Protection Association report NFPA 12-77 (July 1978).